A Performance Enhancement for 60 GHz Wireless Indoor Applications

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Outline

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Overview of 60 GHz WPAN

Standards over 60 GHz WPAN

- IEEE 802.15.3c
- WirelessHD
- WiGig
- ECMA-387
- IEEE 802.11ad

Characteristics of 60 GHz millimeter-wave WPANs

- In-door (<10m)
- Uncompressed HDTV and high rate data transfer
- At least 1 Gbps throughput, 3-4 Gbps preferable

Operating Modes

- Single Carrier: Low complexity and control information
- OFDM: High performance applications

Table: Parameters for OFDM Systems in IEEE 802.11ad

Parameter	Value
Sampling frequency (MHz)	2640
Number of subcarriers	512
Number of data subcarriers	336
Number of pilot subcarriers	16
Subcarrier frequency spacing (MHz)	5.156
Sample duration (ns)	0.38
IFFT and FFT period (ns)	194
OFDM symbol duration (ns)	242

MIMO-OFDM Communication Model

Let y_m be the received decision baseband signal for the *m*th subcarrier

$$y_m = \widetilde{H}_m x_m + n_m, \qquad m = 1, \ldots N$$

where $\mathbf{x}_m$ is the transmitted data symbol, $\mathbf{n}_m$ is the Gaussian noise vector with zero mean and variance σ^2, $\boldsymbol{N}$ is the number of subcarriers, and $\widetilde{H}_m$ represents the frequency response of the equivalent channel matrix for the *m*th subcarrier.

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Maximizing Spatial Diversity

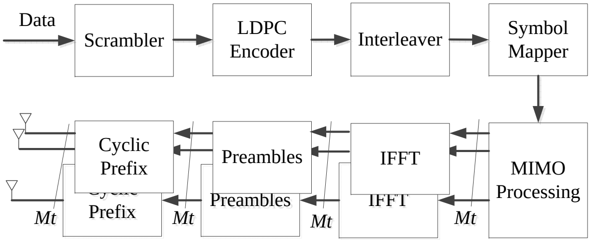

Figure: Block diagram of MIMO-OFDM Transmitter

Space-Time Block Coding

- Enables linear decoding at the receiver
- Transmission matrix $\left[x_1, -x_2^*; x_2, x_1^*\right]$ for a 2×2 architecture

Increasing Spectral Efficiency

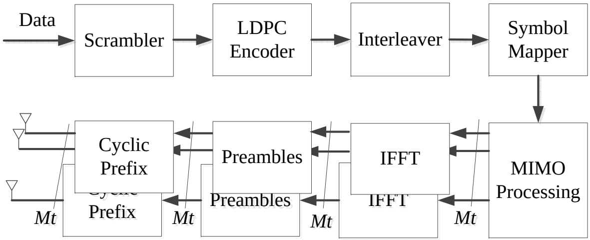

Figure: Block diagram of MIMO-OFDM Transmitter

Spatial Multiplexing

- Doubles the peak data rate for a 2×2 architecture
- Increase the reliability and throughput for lower modes
- Both STBC and SM need an FFT/IFFT per antenna

Optimization Criteria

Recall

$$y_m = \widetilde{H}_m x_m + n_m, \qquad m = 1, \ldots N$$

Here the frequency response of the equivalent channel matrix for the *m*th subcarrier after beamforming $\widetilde{H}_m$ can be is given by:

$$\widetilde{H}_m = c^H H_m w, \qquad m = 1, \ldots N$$

w and **c** are the transmitter and the receiver beam steering vector respectively, and $\mathbf{H}_m$ is the response of the MIMO channel for the *m*th subcarrier.

Optimization Criteria

Maximize Effective SNR

$$\gamma_{eff} = -\beta \ln \left[\frac{1}{N} \sum_{m=1}^{N} \exp\left(-\gamma_m/\beta\right) \right]$$

where γ_m is the symbol SNR experienced on the mth subcarrier, β is a parameter dependent on MCS.

$$\gamma_m = \frac{E\left[\left|c^H H_m w x_m\right|^2\right]}{E\left[\left|n_m\right|^2\right]} = \frac{\left|c^H H_m w x_m\right|^2}{M_t M_r \sigma^2}$$

where M_t and M_r are the number of antenna elements at the transmitter and the receiver respectively. When normalized, $w^H w = M_t$ and $c^H c = M_r$.

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Subcarrier-wise: Maximize SNR on Each Subcarrier

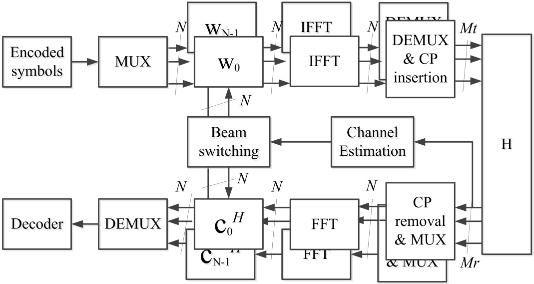

Figure: Block diagram of subcarrier-wise beamforming

$$\gamma_{eff,subcarrier} = -\beta \ln \left[\frac{1}{N} \sum_{m=1}^{N} \exp \left(- \frac{\max_{c,w} \left| c^H H_m w \right|^2}{\beta M_t M_r \sigma^2} \right) \right]$$

Subcarrier-wise: Maximize SNR on Each Subcarrier

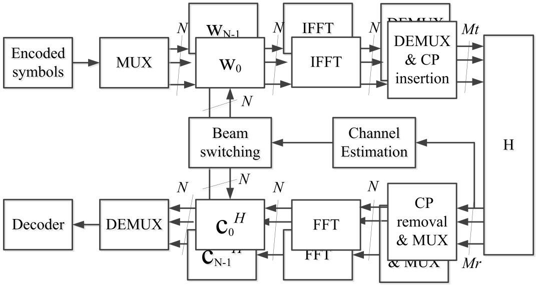

Figure: Block diagram of subcarrier-wise beamforming

Optimal but not practical

- Need full channel state information
- Requires one FFT/IFFT processor per antenna

Symbol-wise: Applies the Same Weight Vector

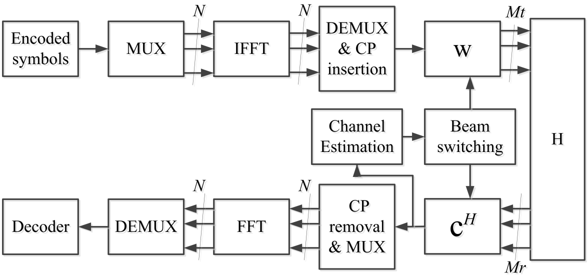

Figure: Block diagram of symbol-wise beamforming

Pre-defined beam codebook

- Full channel state information is not required
- Depends on the number of antenna elements and beams

Symbol-wise: Applies the Same Weight Vector

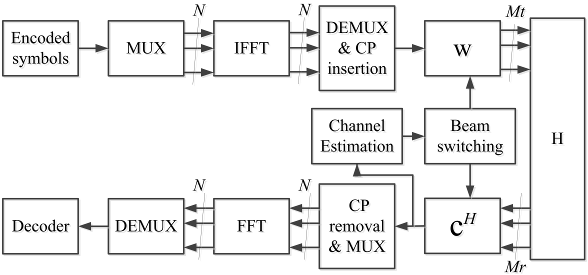

Figure: Block diagram of symbol-wise beamforming

$$\gamma_{eff,symbol} = \max_{c,w \in C} (-\beta) \ln \left[\frac{1}{N} \sum_{m=1}^{N} \exp \left(-\frac{\left| c^H H_m w \right|^2}{\beta M_t M_r \sigma^2} \right) \right]$$

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Hybrid: Compromise the Complexity and Performance

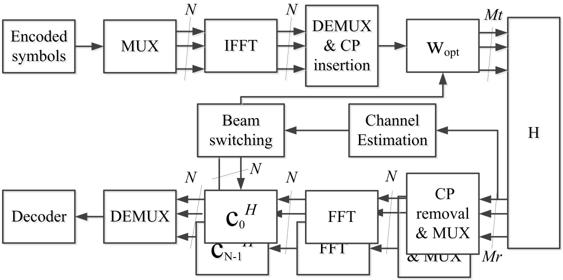

Figure: Block diagram of hybrid beamforming

Symbol-wise at Tx, and subcarrier-wise at Rx

- Optimal each receiver steering vector
- Also use pre-defined codebook

Hybrid: Compromise the Complexity and Performance

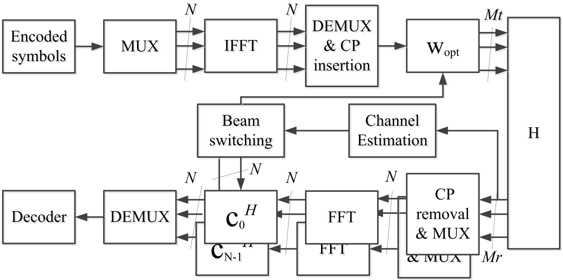

Figure: Block diagram of hybrid beamforming

$$\gamma_{eff,hybrid} = \max_{w \in C} (-\beta) \ln \left[\frac{1}{N} \sum_{m=1}^{N} \exp \left(- \frac{\left| c_{opt}^H H_m w \right|^2}{\beta M_t M_r \sigma^2} \right) \right]$$

Medium Access Control Layer

Hybrid Access

- CSMA/CA: Lower average latency (web browsing)
- TDMA: Better QoS (video transmission)

Sources of Overhead

- Preamble
- Header
- Gap Time
- Acknowledgment Frames

Immediate ACK and Delayed ACK

Figure: Imm-ACK

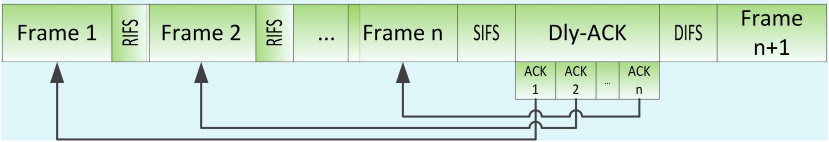

Figure: Dly-ACK

Block ACK and Block NAK

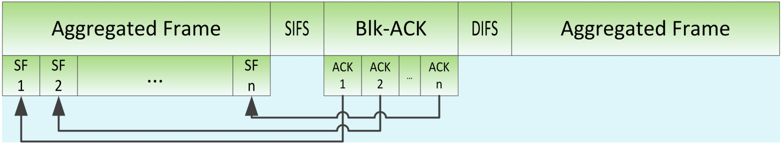

Figure: Blk-ACK

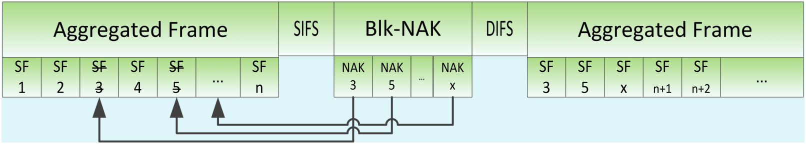

Figure: Blk-NAKs

Preliminaries

System Assumptions

- 1D uniform linear array
- $M_t = M_r = 2$ antenna elements
- Half wavelength isotropic radiators

Channel Assumptions

- Statistic channel from measurements and ray-tracing
- Channel correlation 0.1(low), 0.5(medium) and 0.9 (high)
- Both LOS and NLOS

Preliminaries

Simulation Setup

- Packet Size: 1KB
- PER target: 1%
- Channel Coding: LDPC
- Cyclic Prefix: 128

Table: OFDM Modulation and Coding Schemes

Modulation	Coding Rate	Coded Bits/Symbol	Data Bits/Symbol	Data Rate (Mbps)	SM Data Rate (Mbps)
QPSK	1/2	672	336	1386.00	2772.00
QPSK	5/8	672	420	1732.50	3465.00
QPSK	3/4	672	504	2079.00	4158.00
16-QAM	1/2	1344	672	2772.00	5544.00
16-QAM	5/8	1344	840	3465.00	6930.00
16-QAM	3/4	1344	1008	4158.00	8316.00
16-QAM	13/16	1344	1092	4504.50	9009.00
64-QAM	5/8	2016	1260	5197.50	10395.00
64-QAM	3/4	2016	1512	6237.00	12474.00
64-QAM	13/16	2016	1638	6756.75	13513.50

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LOS Scenario

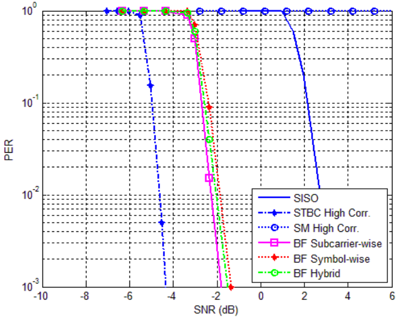

Figure: PER comparison with LOS

- STBC gives about 7 dB gain over SISO system
- All beamforming schemes offer about 5 dB gain
- Spatial Multiplexing is almost unusable

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NLOS Scenario

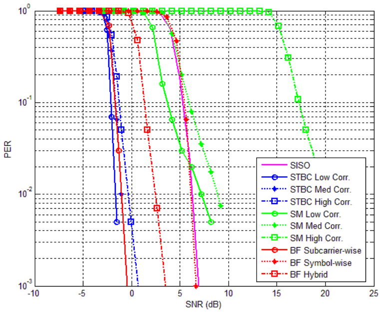

Figure: PER comparison with NLOS

- STBC and SM performance varies depending on the correlation factors
- STBC offers a PER gain of 7-8.5 dB
- SM requires higher SNR than SISO but doubles the data rate
- Hybrid beamforming achieves 4 dB gain

Link Throughput in LOS

Link Adaptation Scheme

- The PHY mode with highest throughput will be selected:

$$Throughput = R(1 - PER)$$

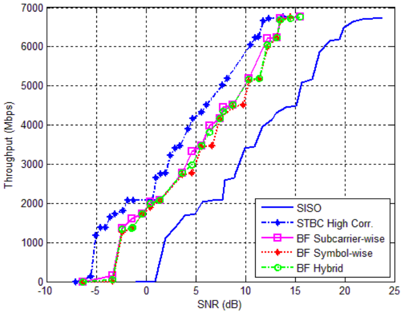

Figure: Link throughput with LOS

- The throughput envelope is the ideal adaptive MCS based on the optimum switching point
- At a certain SNR, MIMO systems outperform SISO system

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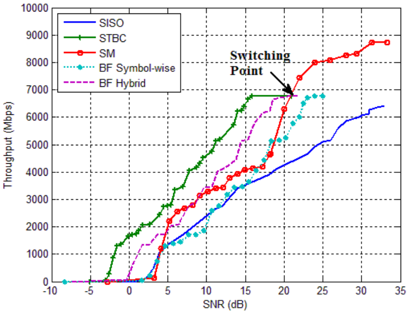

Figure: Link throughput with NLOS

- STBC and hybrid beamforming provide 2-6 dB gain
- More gain can be achieved for very high throughput (>4500 Mbps)
- After the switching point at 21 dB, SM is the best

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Throughput vs BER

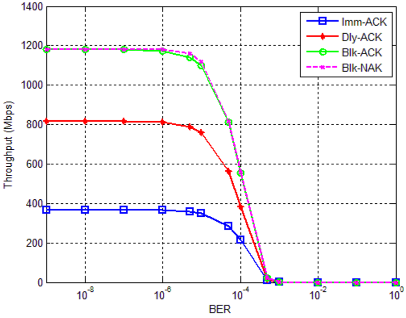

Figure: MAC throughput for different BERs with QPSK 1/2

- Blk-ACK/Blk-NAK increases the MAC efficiency
- BER target should be better than 10^{-3}
- Throughput reaches to the peak when BER better than 10^{-6}

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Max Throughput Achieved for Each Mode

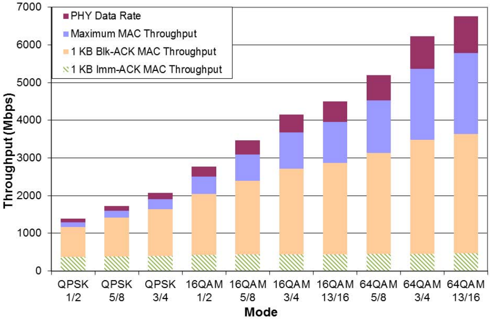


Figure: Max Throughput for Each Mode

- Imm-ACK does not depend on the mode
- While Blk-ACK varies depening on PHY mode
- Imm-ACK efficiency is 6.9%-26%, and Blk-ACK improves by 3-8 times

Operation Range in LOS

Path Loss Model

$$PL(dB) = A + 20\log_{10}(f) + 10n\log_{10}(D)$$

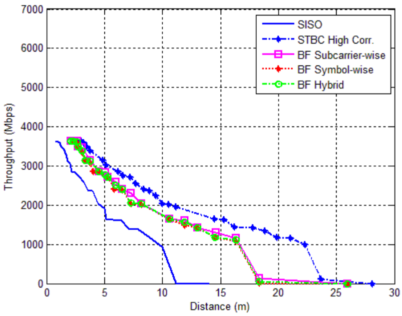


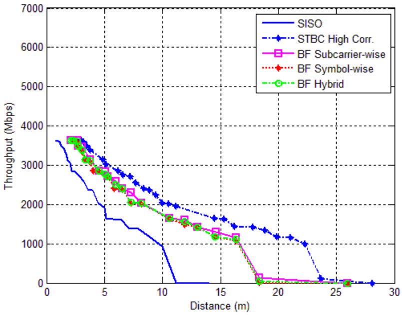
Figure: Operation range in LOS

- The system operates at its maximum throughput when the devices are close
- Adaptively switch to the lower speed when a device moves further away
- Beamforming increase 50% of the tolerance distance, while STBC doubles

Operation Range in LOS

Link Budget Model

$$P_T - PL \geq kTB + NF + ReceiverSNR$$



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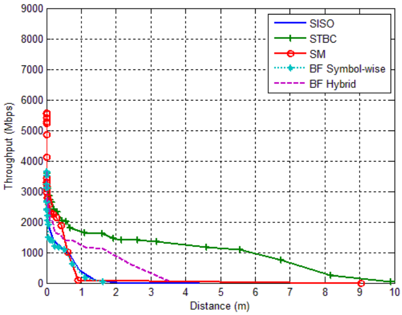

Figure: Operation range in NLOS

- The SISO system could not provide service beyond 1m
- Hybrid beamforming extend the achievable range to 3.5m, and STBC is possible to provide service up to 10m

Summary

- STBC produces the best performance due to its robustness in all conditions; While SM doubles the error-free data rate and increase the reliability for lower MCS modes;
- Beamforming increases the performance significantly. In NLOS, hybrid beamforming provides considerable improvements while maintaining reasonable hardware complexity.
- Frame aggregation and Blk-ACK increase the MAC throughput 3-8 times compared to Imm-ACK

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Thank you! and Questions?

please Email to <x.zhu@Bristol.ac.uk>

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